Laboratory Investigations of Low-swirl Injectors for IGCC Combustion Turbines

R. K. Cheng & D. Littlejohn
Lawrence Berkeley National Laboratory
Berkeley, CA

P.A. Strakey & T. Sidwell
National Energy Technology Laboratory
Morgantown, WV

D.R. Noble & T. Lieuwen
Georgia Institute of Technology
Atlanta, GA

Research funded by U.S. Dept. of Energy, Office of Fossil Energy

Combustion Issues for Ultra-Low Emissions IGCC Gas Turbines

- **Syngas variability**
  - **Compositions vary with gasification processes, feedstocks, and operating conditions**
    - **50-60 % CO, 25-35% H_2, 5-15% CO_2, diluents and trace compounds**
    - **Lower Wobbe indices (i.e. lower heat content) compared to natural gas**
- **High reactivity of H_2**
  - **Burns faster than natural gas**
  - **Low ignition energy**
  - **Wide flammability range**

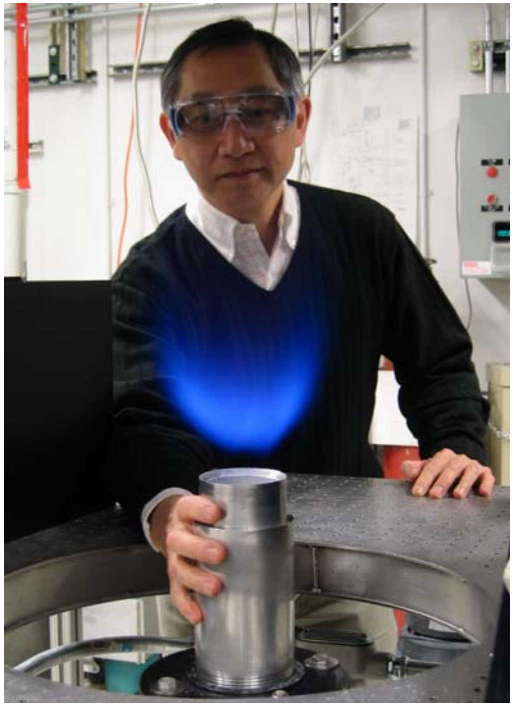
NO_x Control Methods for High-H_2 Gas Turbines

- DOE ATP sets an ambitious target of < 2 ppm NO_x (@15% O_2) at turbine inlet temperature of 2600F
- Two approaches for "air breathing" engines
- Diluted diffusion flame lowers adiabatic flame temperature T_{ad} and address safety issues
  - Large volume of pressurized diluents for the fuel (e.g. steam or N_2)
  - Exhaust gas cleanup may be needed
- Lean premixed flame (dry low-NO_x, DLN) uses air as diluent but presents operational and safety challenges
  - Restricted range of operating conditions due to robust H_2 flames and their flashback tendencies
  - Potential safety risk due to short auto-ignition delay times of H_2 premixtures

Technical Challenges for the Deployment of DLN to IGCC Gas Turbines

- **Open questions on the feasibility of DLN for gas turbine that burns almost pure H_2**
  - Auto-ignition delay at relevant gas turbine conditions remain unresolved
  - Behaviors of H_2 and syngas flames differ than those of natural gas
    - Extending the range of safe operation and reducing flashback risk require fresh approaches for fuel injection, premixing and flame stabilization
- **Consistent combustor performance with changing fuel properties**
  - Potential efficiency/emissions/cost/operability trade-offs to enable transition from syngas to pure H_2 and back
  - Natural gas as a start-up or backup fuel

Objective and Approach



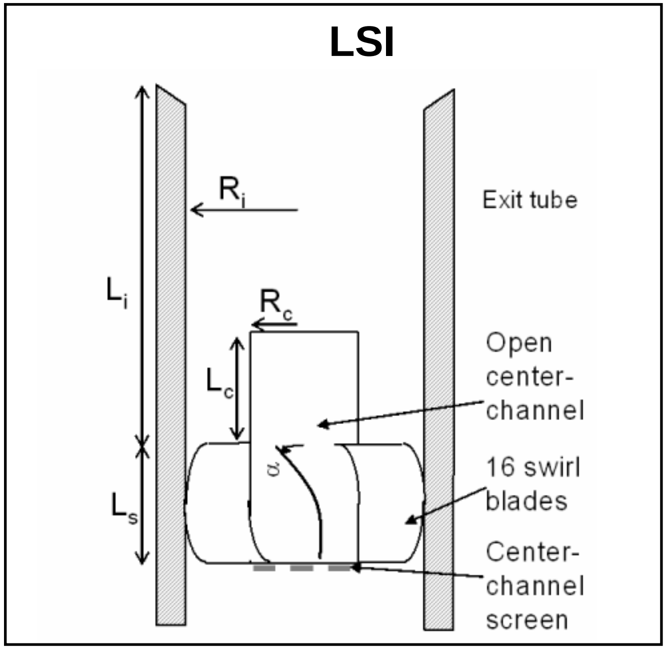
- **Explore the feasibility of a low-swirl Injector concept for IGCC gas turbines**
  - **LSI is a simple, yet sophisticated DLN method to burn gaseous fuels efficiently by a low cost and durable burner**
- **Development approach**
  - **Adapt the LSI for H_2 and verify its operation with syngases and H_2 at gas turbine conditions**
  - **Analyze flame characteristics and apply knowledge to optimize LSI design for H_2 operation**
  - **Investigate flashback mechanisms and develop preventive and recovery remedies**
  - **Address auto-ignition through LSI sizing and premixer design**
  - **Communicate insights to OEMs**

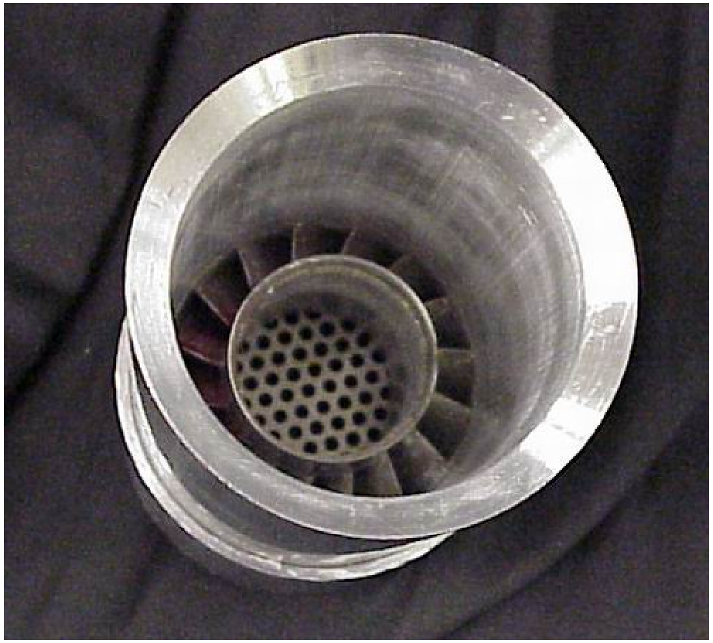
LSI Background

- **Low-swirl injector utilizes a novel flame stabilization concept that is radically different than conventional approaches**
  - **Spin-off from basic research on premixed turbulent flames**
  - **Operating principle deduced from experimental observations & analyses**
  - **New research topic not covered by combustion text books**
- **Proven technology for heating and power systems**
  - **Great attributes:**
    - **Scalable - 7 kW (1”) to 14 MW (24”) burners due to linear characteristics**
    - **Robust - < 2 ppm NO_x (@15%O_2) without steam injection, exhaust gas clean-up or tight controls for mixing and operational conditions**
    - **High Performance – excellent turndown (30:1), fuel flexible, and reliable**
    - **Low-cost - simple design made of conventional materials, size & form compatible with current designs**
- **Scientific foundation to guide developments**
  - **Good understanding of the flame anchoring mechanism and the flame behaviors**
  - **Analytical model for adaptation to fuel-flexible systems**

LSI Has a Relatively Simple Design

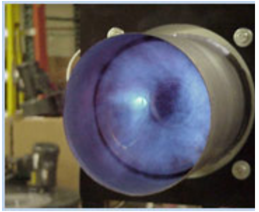
- Reactants pass through two passages – swirled and unswirled
- Non-swirling core inhibit flow recirculation
- Perforated screen covering center channel balances the ratio between swirling and non-swirling portions
- Flame propagates freely in the divergences flow downstream of the nozzle





Maxon Corp Has Two Lines of Low-swirl Burner Products

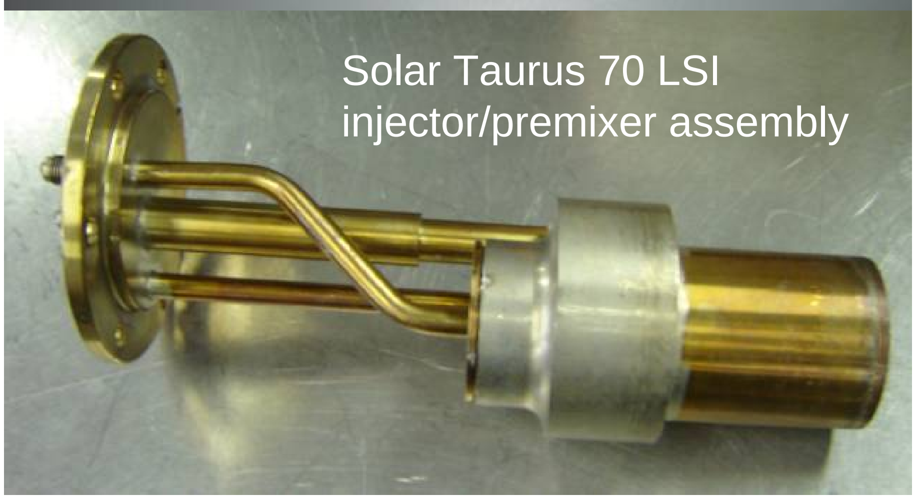
- **Highly reliable 4-7 ppm NO_x (@3% O_2) = 1.5-2.5 ppm NO_x (@15% O_2) operation**
- **M-PAKT burners (0.5 – 3.5 MMBtu/hr) available since 9/03**
  - **2”, 4” and 6” burner diameter**
  - **Fuel flexible with natural gas, propane and butane**
  - **10:1 turndown without pilot assistance**
  - **Hundred of units installed**
  - **Improve product quality (paint curing & food processing)**
  - **1st unit operating continuously since 2/02**
- **OPTIMA SLS gas/liquid dual-fuel burners (12 - 50 MMBtu/hr) introduced in 2006**
  - **8”, 10”, 12”, 16”, 20” and 24” burner diameters**
  - **enhanced 13:1 turndown**
  - **backup liquid fuel firing**
  - **Two prototypes installed & several units in production**



26” burner
(44 MW, 150 MBtu/hr)

SLS™
shear layer stabilization

Developed LSI for 7 MW Gas Turbines



- **Drop-in replacement for Solar Taurus 70 engine**
  - **≈7690 kW (10,310 hp) 16:1 compression ratio**
  - **3 – 4 % ΔP**
  - **Annular liner fitted with 12 injectors**
  - **Demonstrated engine readiness and low impact on engine performance**
    - **Good operability (light-off, loading & unloading protocol, response to off-design conditions)**
    - **No unacceptable combustion oscillations**
    - **< 5 ppm NO_x**

Laboratory Studies to Support IGCC Developments

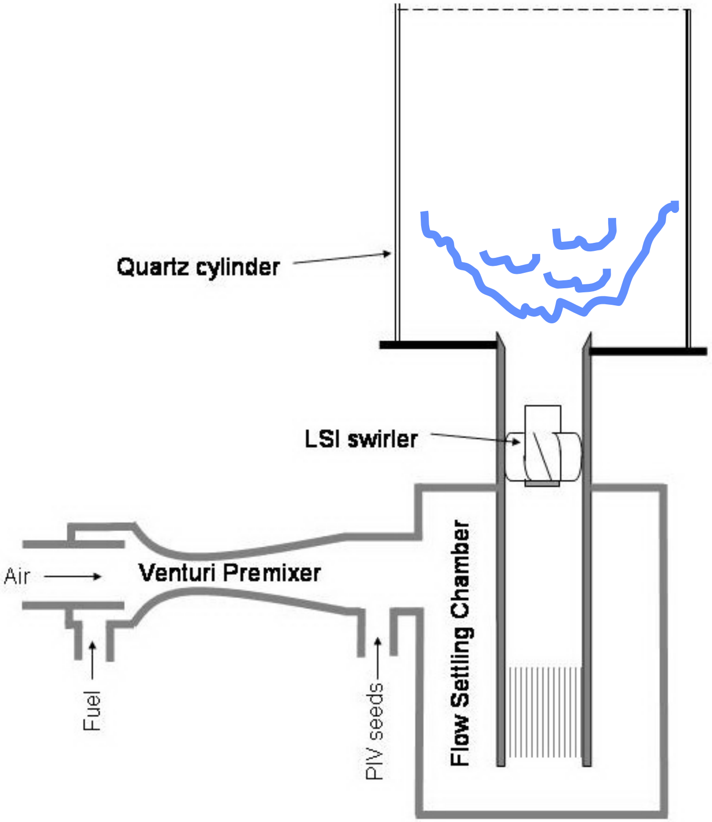
- **Verify operability of LSI with syngases and H_2 at STP**
- **Laser measurements to characterize flowfields and behaviors of syngas and H_2 flames**
  - **Define key parameters**
  - **Develop analytical model for the coupling between the syngases and H_2 flames and their flowfields**
- **Design LSI prototypes for syngases and H_2**
  - **Verify operations at STP and emissions at high temperatures and pressures**
- **Development of computational design tools for refinements and adaptation to engines**
  - **CFD and LES methods for flowfield calculations**
  - **DNS methods for H_2 flame modeling**

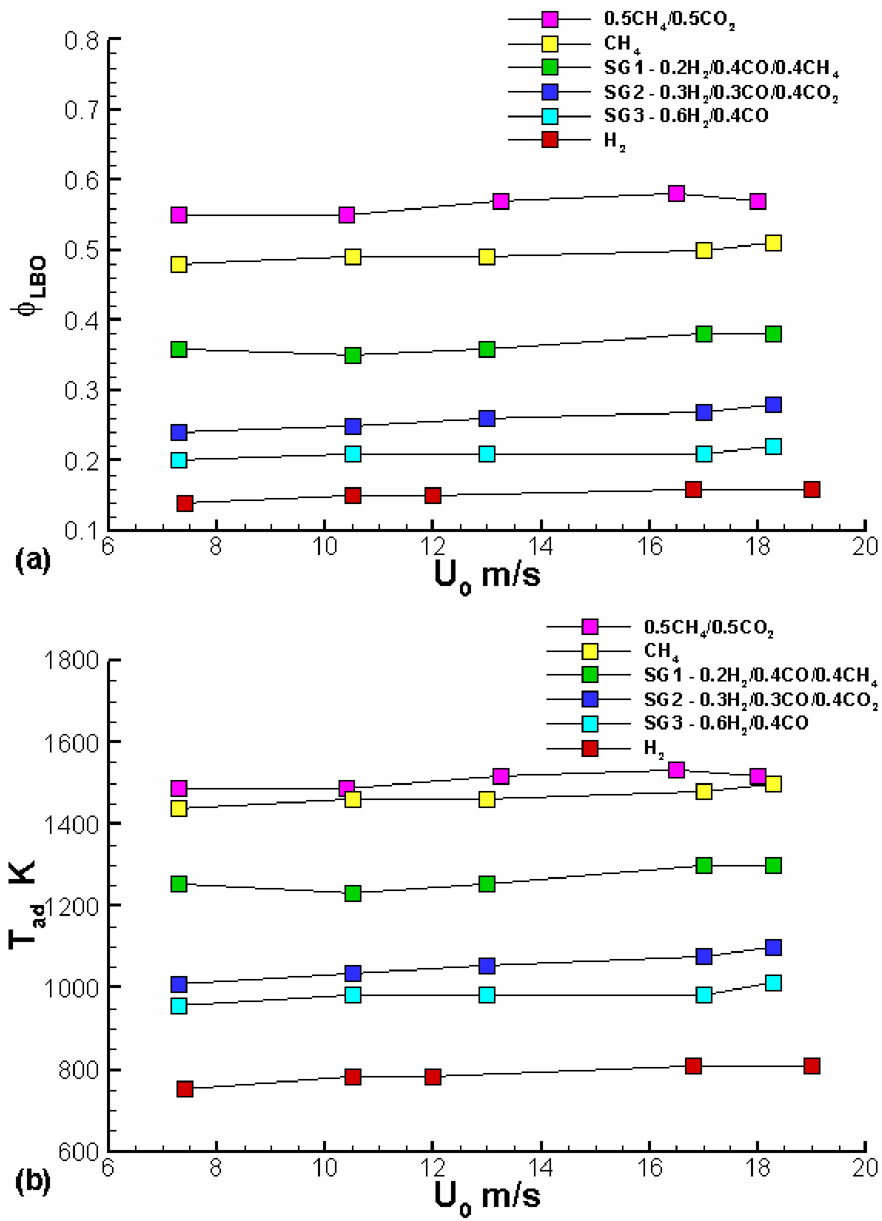
Overview of Results from These Publications

1. Cheng, R. K. and D. Littlejohn (2008). "Laboratory Study of Premixed H2-Air & H2-N2-Air Flames in a Low-swirl Injector for Ultra-Low Emissions Gas Turbines." Journal of Engineering for Gas Turbines and Power In press: also ASME GT2007-27512.
2. Cheng, R. K. and D. Littlejohn (2008). “Effects of Combustor Geometry on the Flowfields and Flame Properties of a Low-Swirl Injector” Turbo Expo 2008, Berlin, Germany, ASME GT2008-50504
3. Littlejohn, D., R. K. Cheng, D. R. Noble and T. Lieuwen (2008) “Laboratory Investigations of Low-Swirl Injectors Operating with Syngases” Turbo Expo 2008, Berlin, Germany, ASME GT2008-51298
4. Cheng, R. K., D. Littlejohn, Strakey, P. A., and T. Sidwell (2008) “Laboratory Investigations of a Low-swirl Injector with H_2 and CH_4 at Gas Turbine Conditions” Submitted to Proc. Comb. Inst.

Apparatus, Diagnostics & Analysis for STP Experiments

- **LSI mounted on the plenum and premixer of an industrial burner**
- **Applied PIV to atmospheric open and enclosed flames**
- **Deduced mean, rms velocities, Reynolds stresses & turbulent flame speeds**
- **Measured NO_x and CO emissions**



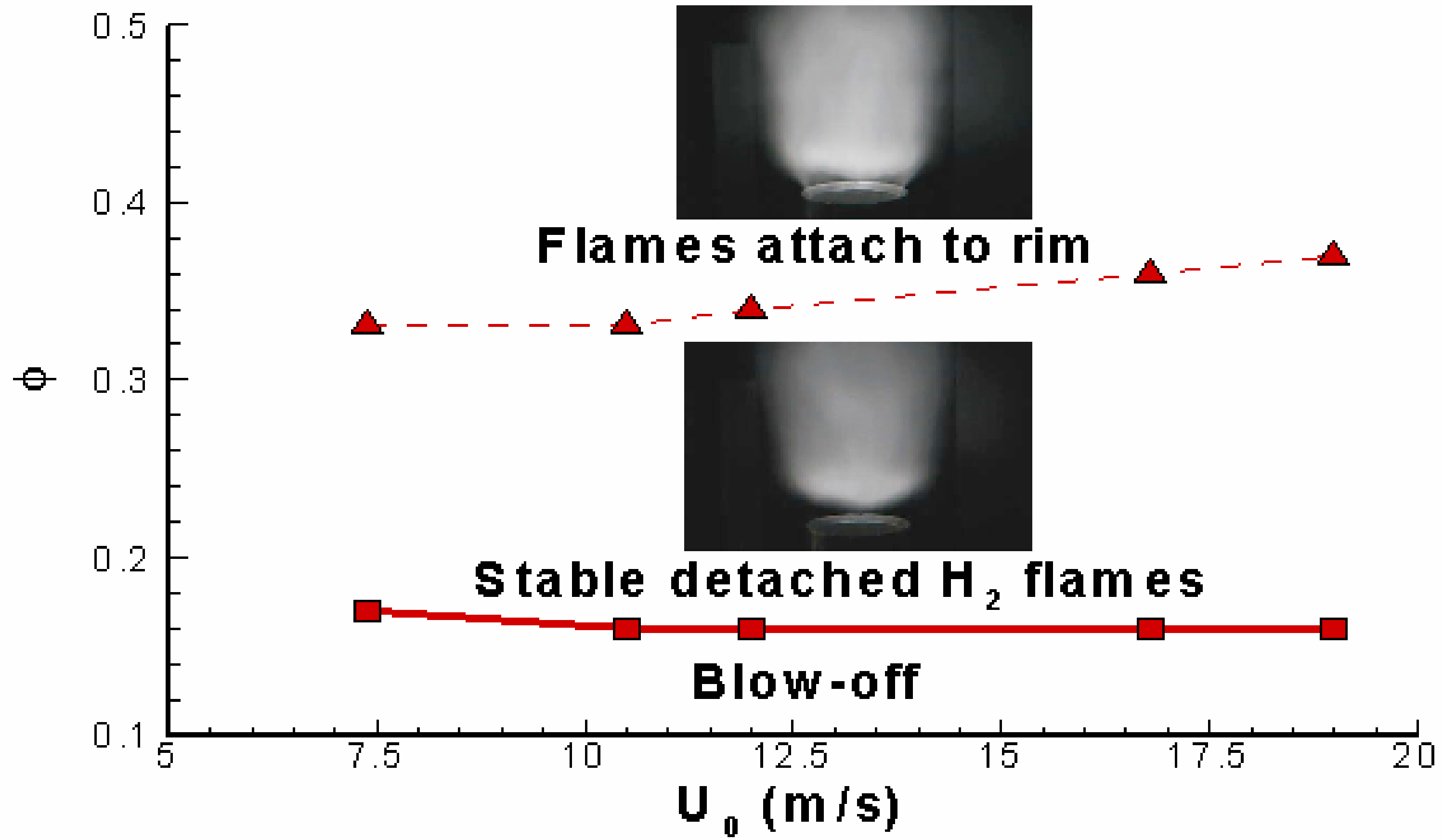


LSI for Natural Gas Accepts Syngases and H_2 without Requiring Significant Modification

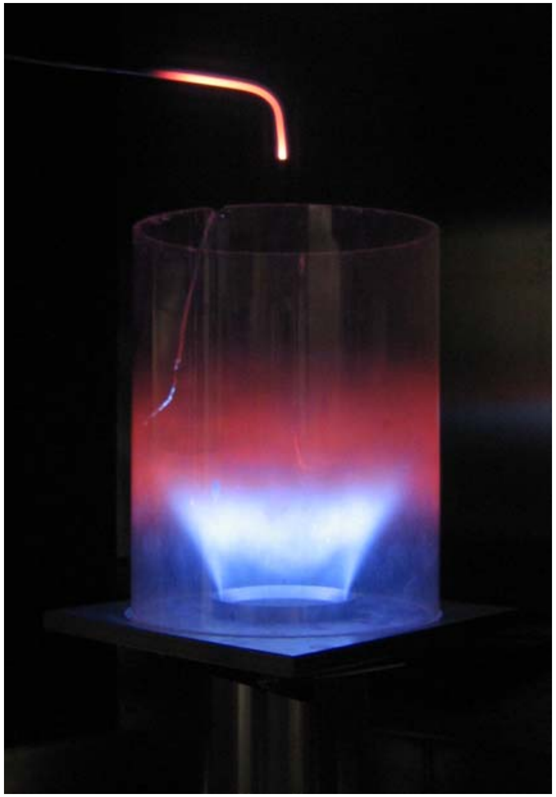
- **Compared lean blow-off, emissions and velocity flowfields with natural gas flames**
  - **LBO insensitive to U_0**
  - **Increase H_2 fuel concentration extends LBO to lower flame temperatures**
  - **NO_x emissions show log-linear dependency on adiabatic flame temperature T_{ad}**

High Diffusivity and Reactivity of H_2 Changes Flame Shape at Higher ϕ

- **Flame attachment can alter flame flowfield and the flame stabilization (or anchoring) mechanism**



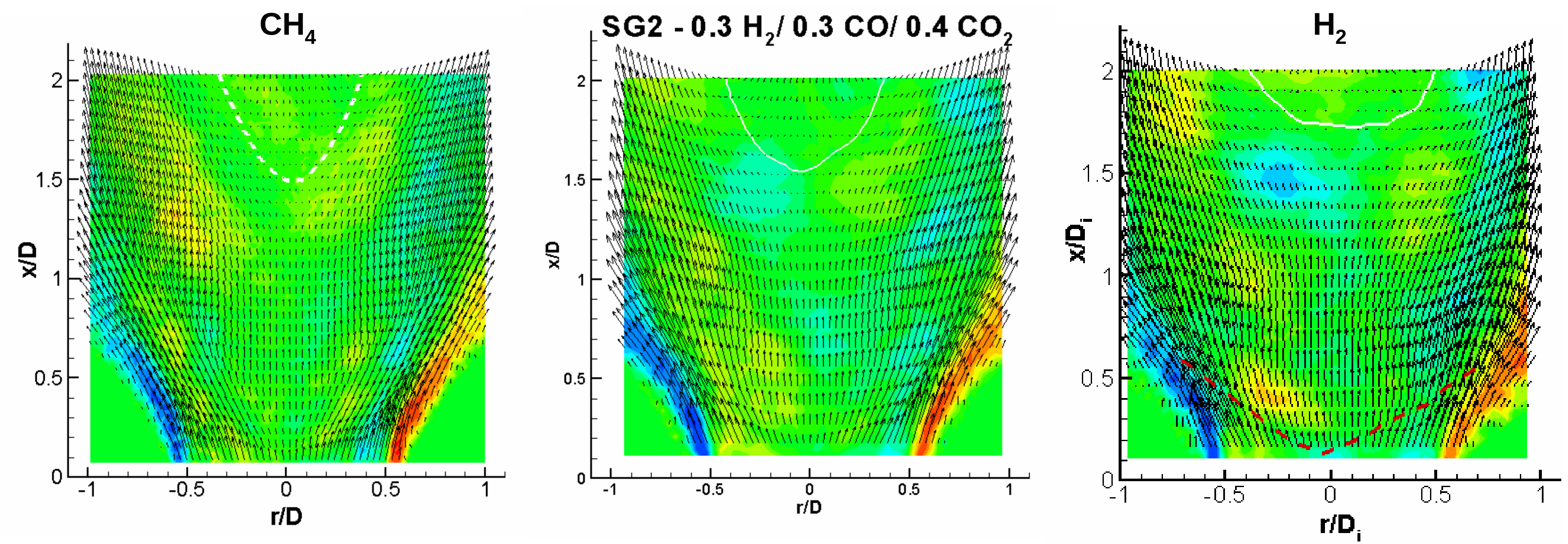
Relaxing Swirl Number to Optimize for H_2 Flames



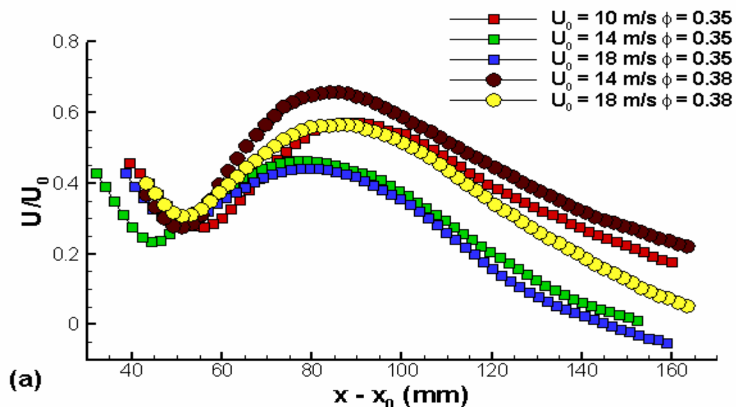
- Lowering swirl number from 0.54 to 0.43 generates more lifted flames and postpones flame attachment to $\phi = 0.4$ when flames are not enclosed
  - LSI with S = 0.51 offers best performance for laboratory studies
  - LSI for H_2 is not significantly different than LSI for hydrocarbons
- Corner recirculation zone formed at the combustor entrance promotes H_2 flame attachment
  - Eliminating the sharp corner with a diffuser cone is a solution to mitigate H_2 flame attachment

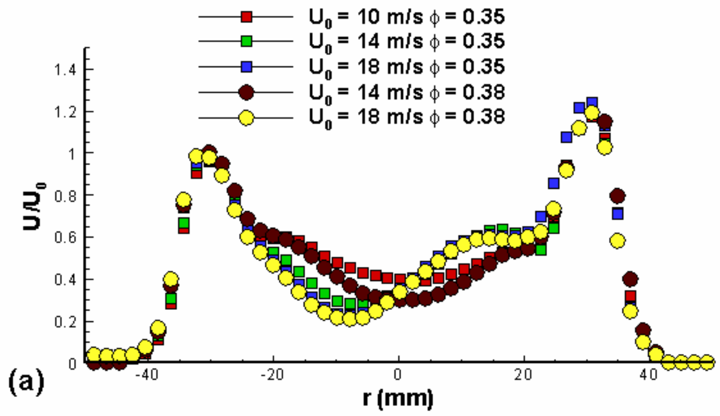
Flowfields of CH_4, syngas and H_2 Flames Have Similar Features

- All lifted flames show near-field flow divergence and far-field weak recirculation zone
- Flowifled features unchanged in combustor of optimum size
- Fully attached H_2 flames are the exceptions



Syngas and H_2 Flames Exhibit Nearfield Self-Similarity as in NG Flames





Self-similarity means the axial (top) & radial (bottom) velocity profiles have consistent trends

- **Four parameters from the mean centerline profile for an analytical model that describes the flame anchoring mechanism**

$$1-\frac{dU}{dx}\frac{(x_f - x_o)}{U_o} = \frac{S_T}{U_0} = \frac{S_L}{U_0} + \frac{Ku'}{U_o}$$

  Virtual origin, x_0

  Normalized divergence rate, a_x

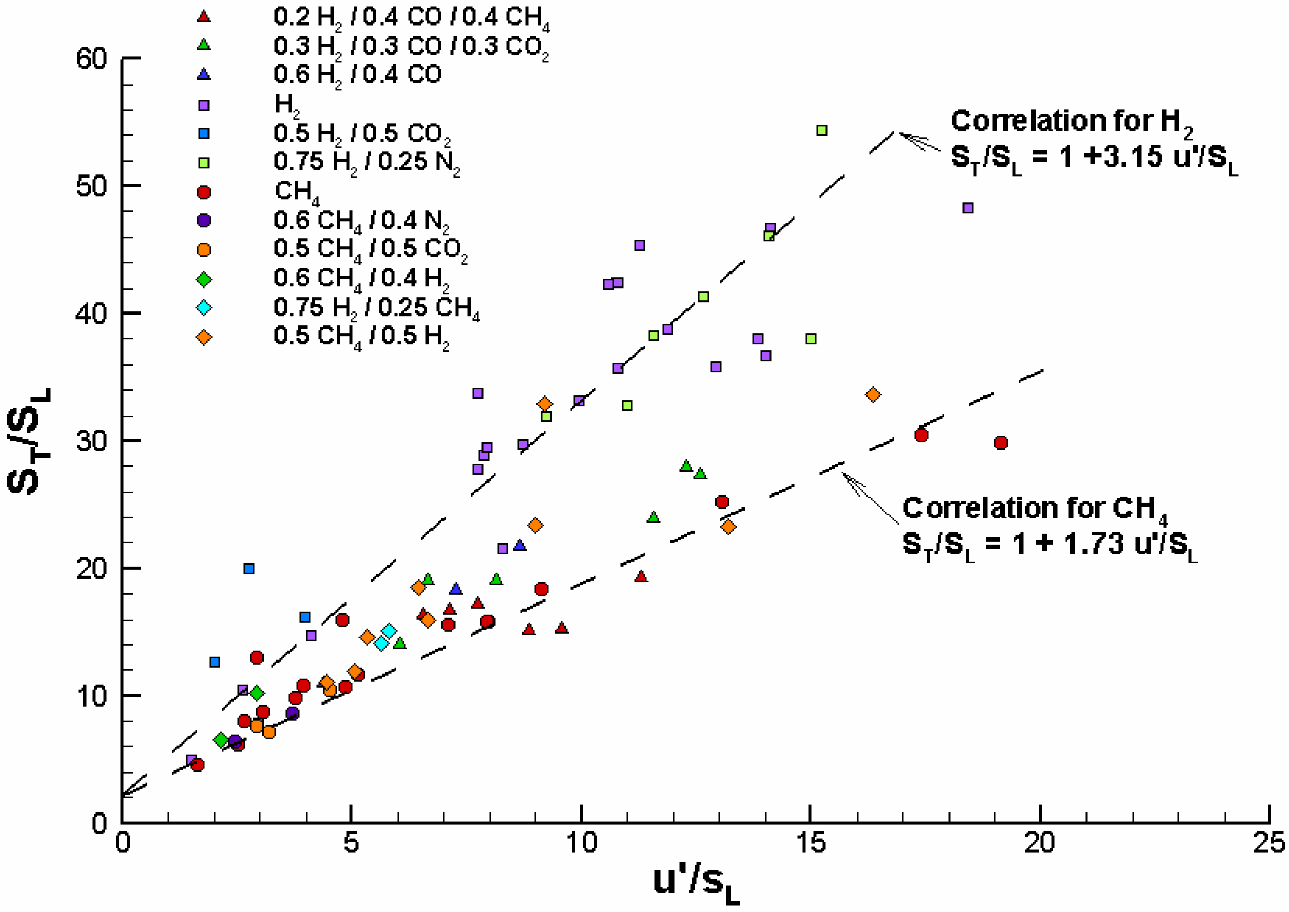
  Flame position, x_f

  Turbulent flame speed, S_T

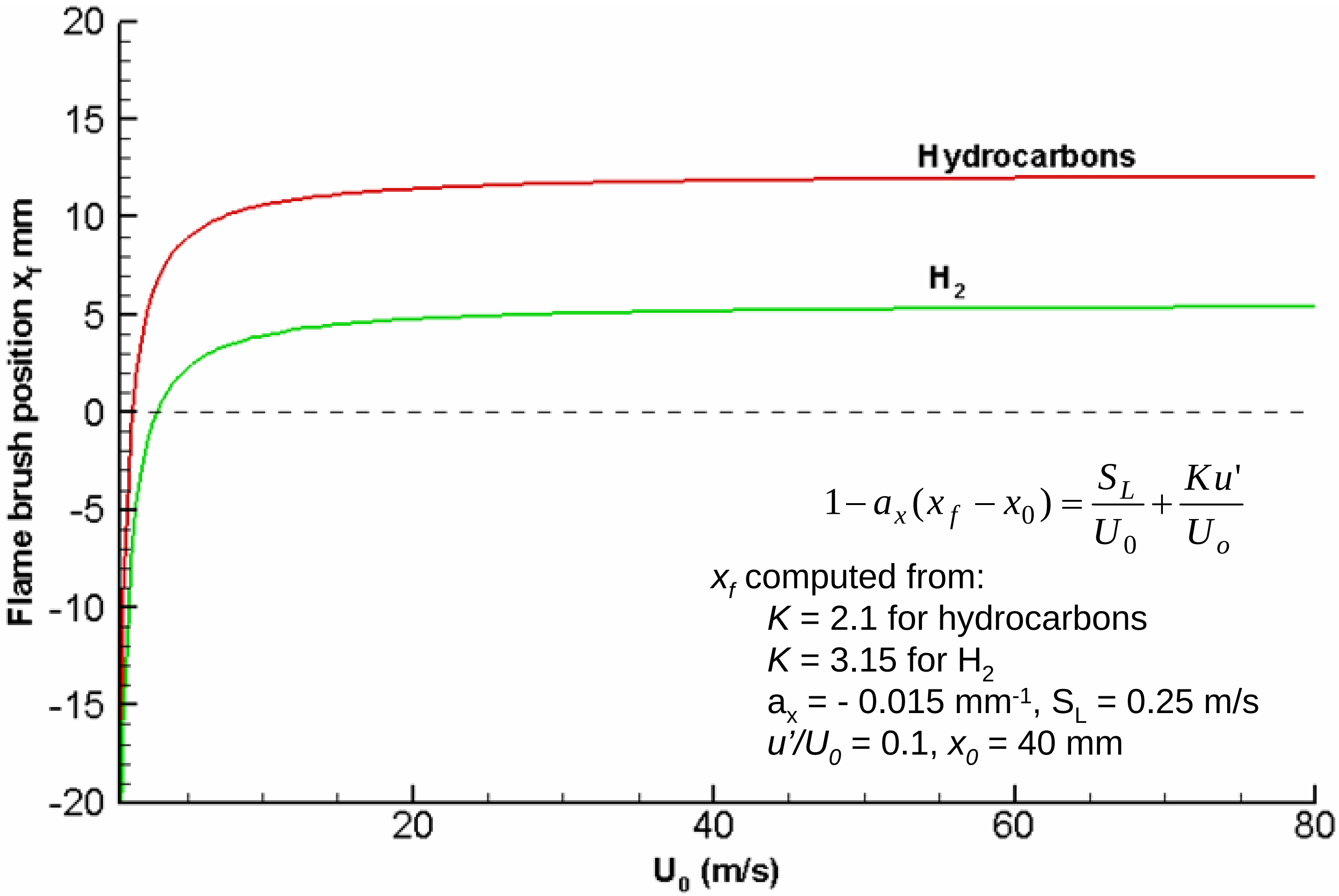
- **Fuel effects expressed through the correlation constant *K* for the turbulent flame speeds**

Turbulent Flame Speeds of H_2 and Hydrocarbons Correlate Linearly with u'

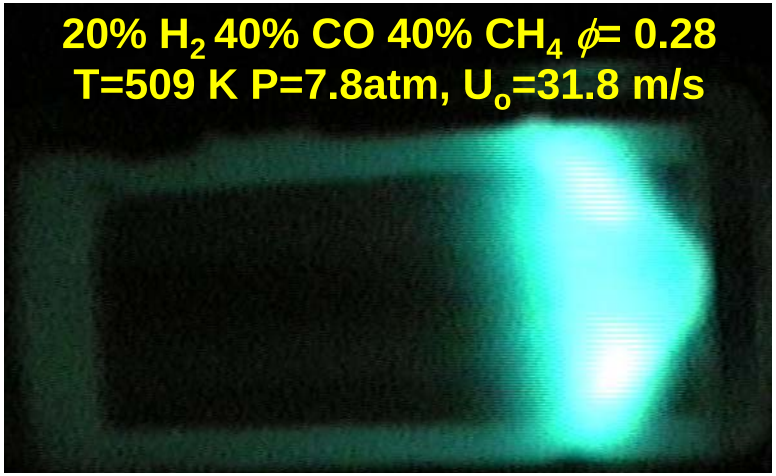
- **Turbulent flame speeds for H_2 about 50% higher than hydrocarbons**
- **Syngas turbulent flame speeds are in-between**

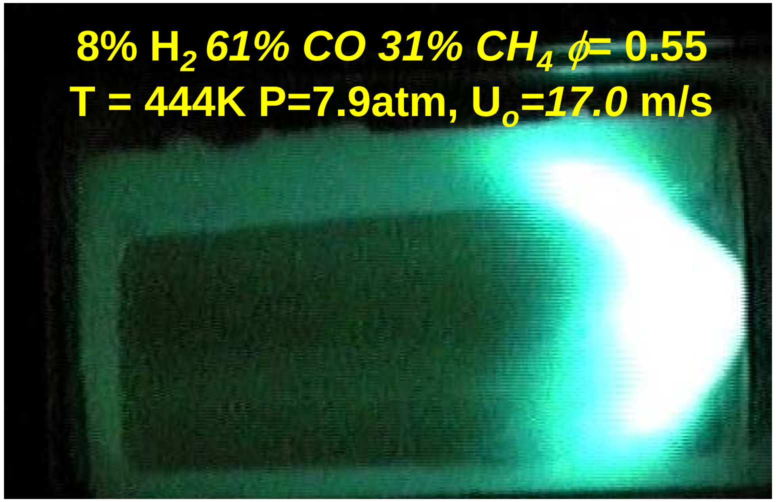


Higher H_2 Flame Speeds Means an Upstream Shift of the Flame Position

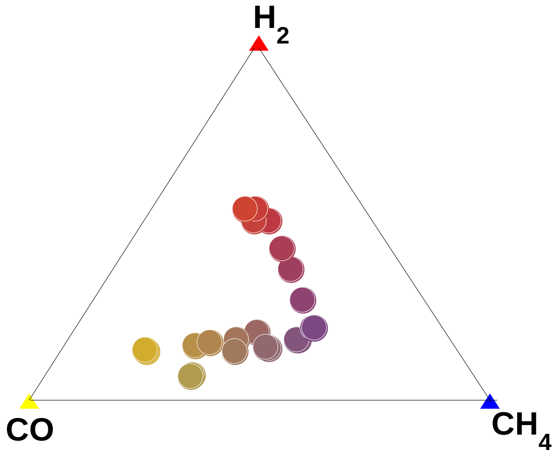


Verify High-Pressure Syngas Operation at Georgia Tech

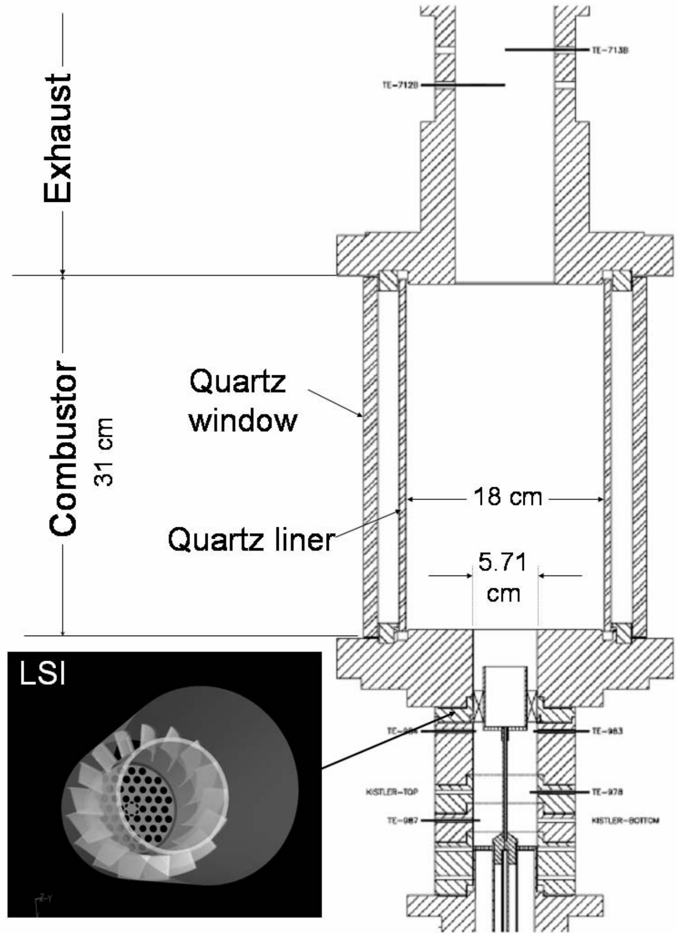




- **Small 1” LSI evaluated in a pressurized combustion vessel**
- **Explored various syngas operation at 330 F < T < 466 F and P = 8 atm**



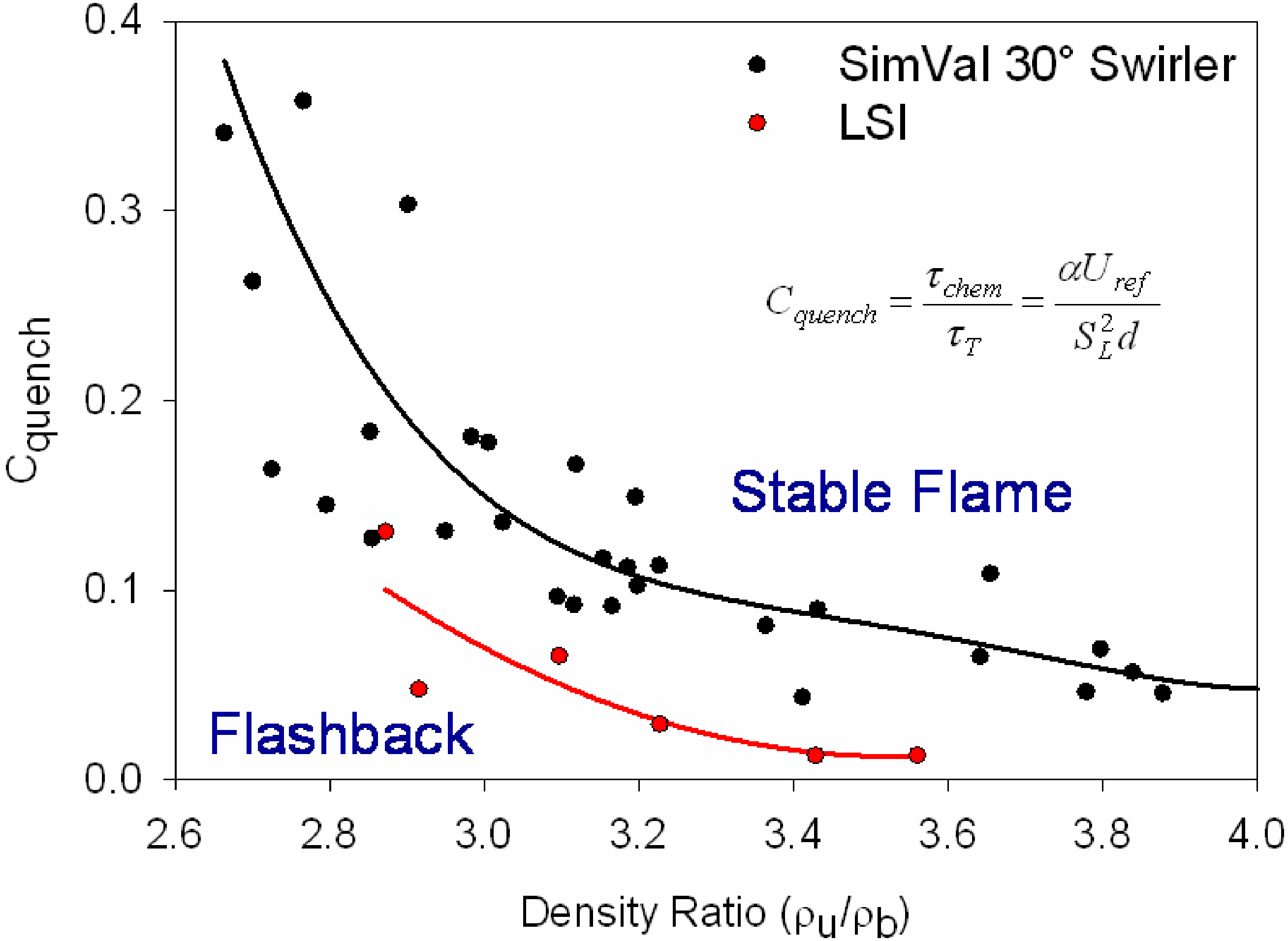
LSI Evaluated in SimVal Facility at NETL Morgantown



- **SimVal has an optically accessible combustor designed for validation of numerical simulations**
- **Optimized LSI for H_2 with 5.84 cm ID and swirl number S = 0.5**
- **Operated with natural-gas/H_2 blends with H_2 from 0 to > 98%**
- **Determined flashback, emissions and observe overall flame properties at 500 < T < 600 K, 2 < P < 8 atm and 20 < U_0< 60 m/s**
- **First independent evaluation of LSI at elevated T and P**

LSI Less Prone to H_2 Flame Flashback Than Idealized High-Swirl Design

- **Flashback appears to originate at central shear region at the boundary of the swirled and the unswirled flows**



Changes in Flame Positions and Flame Shapes at Elevated T & P are Same as at STP

- **Flame shifts upstream and attaches to the rim with increasing $H_{2\%}$**
- **Implies similar flame/flow interaction processes and anchoring mechanism**

4 atm
550F

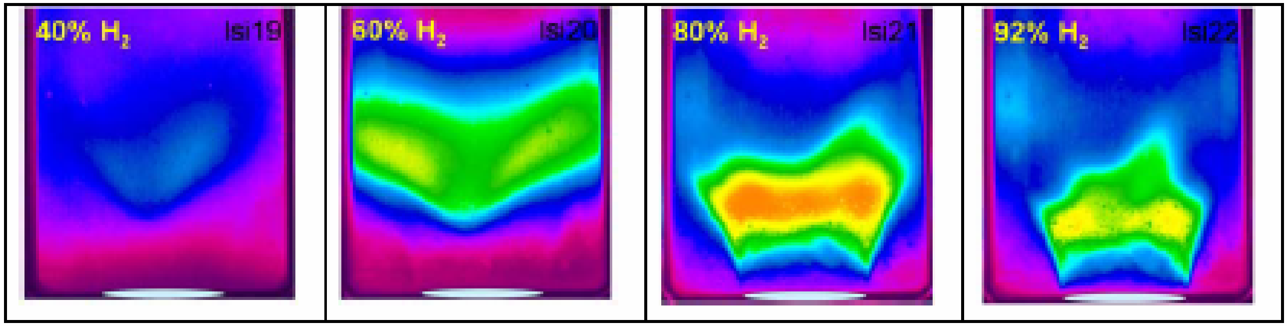


Figure 1 Visible luminosity of CH_4/H_2 flames at 4 atm, $\phi = 0.4$ and $U_0 = 40$ m/s

1 atm
70F

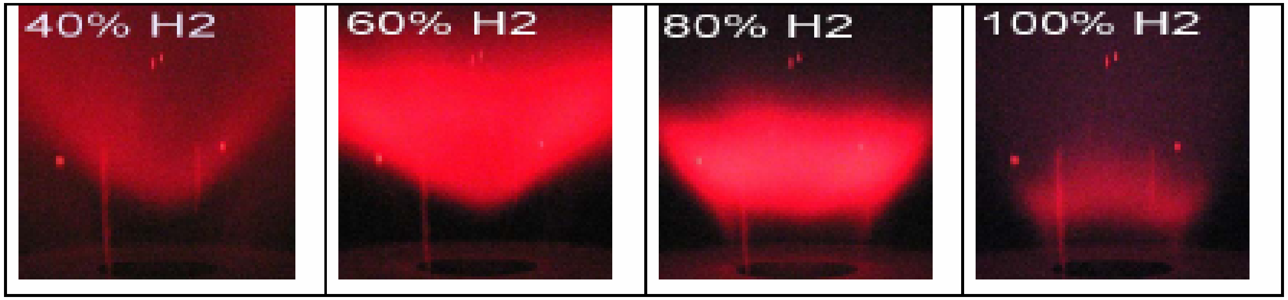
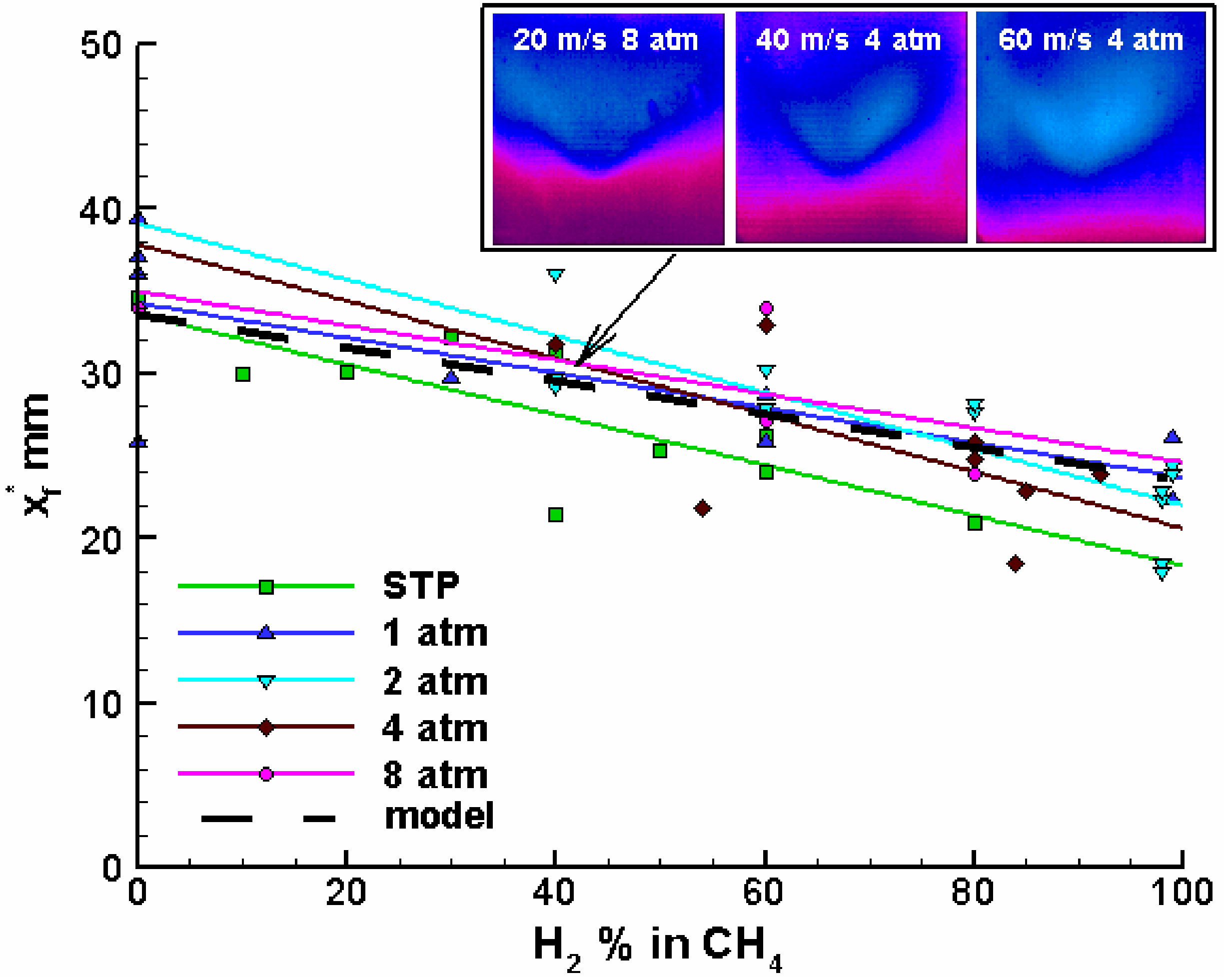


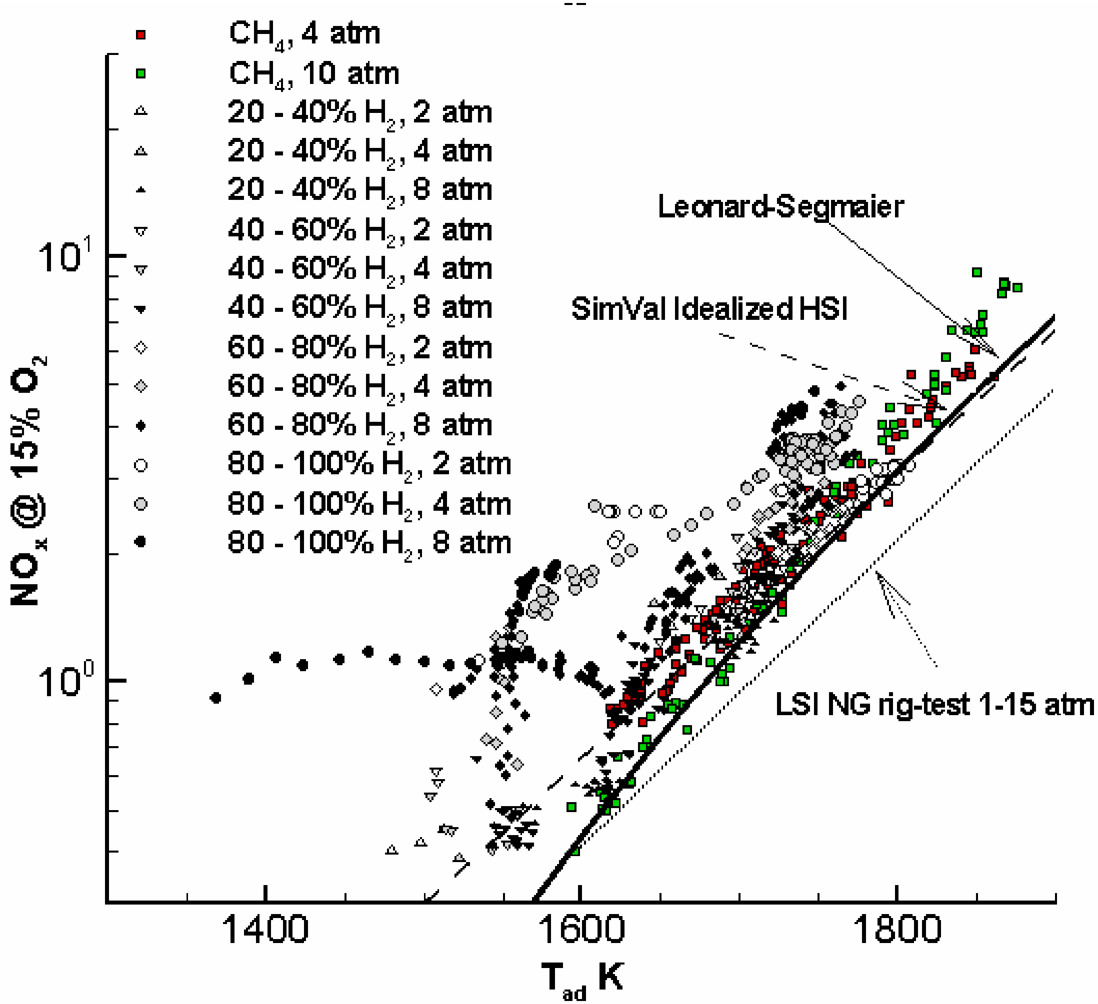
Figure 2 Visible luminosity of CH_4/H_2 flames at STP, $\phi = 0$-.4 and $U_0 = 20$ m/s

Flame Shifts Consistent with Modeling Prediction



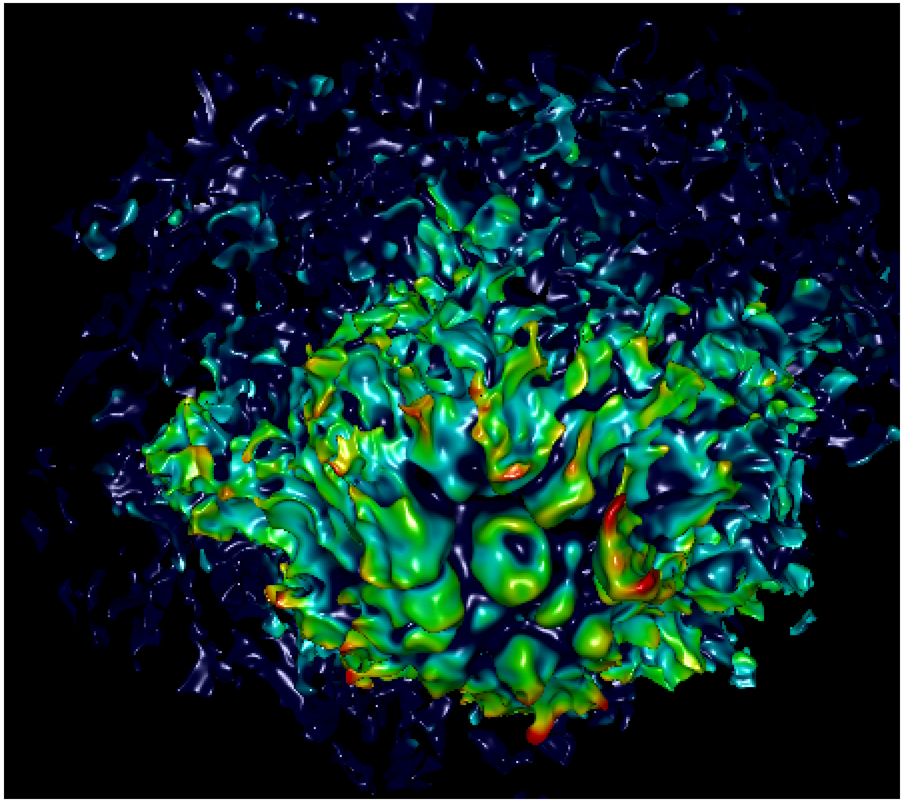
- Flame position insensitive to U_0
- Flame shifting upstream at high H% due to higher flame speed correlation coefficient K

SimVal Data Verified Log-Linear Dependency of LSI NO_x on T_{ad}



- NO_x emissions consistent with a well-designed combustion system
- NO_x emissions from LSI independent of the hardware configuration
- 2 ppm NO_x at T_{ad} = 1700K with close to pure H_2
- Leveling of NO_x for pure H_2 flames at T_{ad} < 1600K needs further studies

Collaborate with Computational Research on H_2 Premixed Turbulent Flames For Gas Turbine Development



Simulated T = 1200K contour of H_2 LSI flame shows non-uniform local fuel consumption. Peak values (red) are approximately 3.5 times the laminar burning velocity.

- LBNL Center for Computational Science and Engineering specializes in large domain 13 cm^3 direct simulation (DNS) of turbulent premixed flames
- Recent award to focus on H_2 combustion problems relevant to IGCC
  - Investigate H_2 turbulent flame speed mechanisms
  - Improve H_2 model for CFD and LES
  - Provide insight into NO_x formation at low T_{ad}

Laboratory Studies Show LSI Amenable to Burning Syngases and Pure H_2

- **Dominant flame/flow coupling and anchoring processes of H_2 and hydrocarbon flames are the same**
  - **Effects due to high diffusivity are impediments to open flame laboratory studies and can be addressed by avoiding the use of sudden expansion at nozzle discharge**
- **Higher H_2 flame speed can be accommodated by a small reduction of the LSI swirl number or by staging**
  - **Demonstrates the applicability of the analytical model for H_2 LSI design**
- **Encouraging results to guide hardware refinement for further evaluation at IGCC turbine conditions**

Planned Activities

- **Apply knowledge to optimize LSI design for H_2 operation**
  - Integration of conical nozzle discharge to mitigate corner recirculation effects on flame attachment
- **Investigate flashback mechanisms and develop preventive and recovery remedies**
  - Lower of swirl vane angle and optimize vane shape to reduce shear stresses and the potential for generating vortex breakdown
  - Reduce drag coefficients of all LSI components to control turbulence and flame anchoring to premixer
- **Address auto-ignition through LSI sizing and premixer design**
  - Optimize residence time of premixture and explore premixing schemes
- **Development of computational design tools**
  - Evaluate the fidelity of CFD calculations and assist in the development of advanced LES and DNS methods
- **Fundamental understanding of H_2 flame processes**
  - Flowfield and turbulent flame speeds measurements at gas turbine conditions to verify analytical model for flame anchoring mechanism
  - Collaborate with DNS developer on lean premixed H_2 flame models